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Article

Integrating Community Driven-approach and CSR-supported Coastal Defense: Waste-tire Wave Breakers (APO) in Tanjung Pakis West Java

Mochammad Rizqy Maulana[1,*], Dhavani Ardyas Putera [1,2], and Muhammad Bima Oktageannar[1,]

[1] CarbonEthics, Jakarta 12160, Indonesia
[2] Department of Geography, Universitas Indonesia, Depok 16424, Indonesia
* Correspondence: maulana@carbonethics.org

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Abstract: Coastal erosion along the northern coast of Java poses significant environmental and socio-economic challenges, particularly due to mangrove conversion into aquaculture. In Tanjung Pakis, West Java, the community group of Elang Laut, in collaboration with CarbonEthics and Planet Ban, implemented waste-tire wave breakers (Alat Pemecah Ombak, APO) as a community-driven coastal protection strategy supported by a CSR-based circular economy model. This study evaluates APO effectiveness by integrating multi-temporal shoreline analysis using Sentinel-2 imagery and the Digital Shoreline Analysis System (DSAS) for 2018–2024, combined with socio-economic surveys and focus group discussions. The analysis shows that post-installation (2022–2024), mean shoreline erosion decreased by 4.73 m/yr, while accretion increased by 2.85 m/yr, reducing overall shoreline retreat from −9.79 m/yr to −5.41 m/yr. Impacts were concentrated in APO-installed areas, indicating effective wave attenuation and sediment trapping. Socio-economic impacts findings reveal an average 11.1% increase in household income, driven by improved fishpond protection and productivity. CSR support enabled construction, maintenance, and local labor involvement, strengthening community ownership. The study demonstrates that APOs are most effective as complementary measures to ecosystem-based restoration. Combined with community participation and CSR support, APOs offer a viable hybrid approach to enhancing coastal resilience in vulnerable tropical environments.

Keywords: waste-tire wave breakers; community-based coastal protection; Corporate Social Responsibility (CSR)

1. Introduction

Climate change continues to have a profound impact on coastal communities worldwide, with the northern coastline of Java Island being among the most affected. Tanjung Pakis village, located on the northern coast of Karawang Regency, exemplifies the environmental vulnerabilities and social challenges faced by many coastal settlements in Java. This village is experiencing severe coastal erosion, unpredictable weather patterns, and ongoing degradation of coastal ecosystems. A major cause of this vulnerability is the conversion of natural mangrove forests into shrimp and fish aquaculture ponds over the past five decades (Arifanti *et al*., 2022; Haryani, 2022).

The loss of mangroves has eliminated natural coastal protection and critical ecosystem services. Historically, mangrove forests have served as carbon sinks, shoreline stabilizers, and biodiversity refuges. Ambariyanto *et al*. (2023) emphasize that mangrove ecosystems not only store carbon in biomass and sediments but also reduce the risks of tidal flooding, saltwater intrusion, and storm surges. However, research in Indonesia's coastline changes from 1990 to 2018 (Sagala *et al*., 2024) reported a reduction of 5,995.52 km of natural coastline, alongside an increase of 6,771.92 km of artificial coastline. Mangrove areas were among the most severely affected by this erosion event. Among all provinces in Indonesia, West Java experienced the most severe erosion of mangrove areas (Sagala *et al*., 2024). The deforestation of mangroves thus imposes a dual burden: heightened coastal hazards and the release of stored carbon into the atmosphere, exacerbating greenhouse gas concentrations.

Currently, Tanjung Pakis is home to approximately 6,060 residents (Badan Pusat Statistik Karawang, 2023) who largely depend on small-scale fisheries and aquaculture. Coastal erosion damages essential infrastructure, including roads, settlements, and public facilities, while threatening the livelihoods of fishers and farmers (Haryani, 2022). The combination of ecological degradation, socio-economic vulnerability, and limited institutional support makes communities like Tanjung Pakis highly susceptible to climate-related risks (Martuti *et al*., 2022).

In response to the severity of coastal erosion and the urgency of restoring ecosystem functions, various technical and ecosystem-based approaches have been tested in Indonesia. One promising innovation is the APO, a locally constructed structure made from used tires that serves as a low-cost adaptive solution to dissipate wave energy and facilitate sedimentation. Compared to conventional concrete seawalls, APO installations are more technically and financially feasible for local communities. Nevertheless, challenges remain in ensuring long-term sustainability and scalability, particularly with respect to community ownership, continuous funding, and technical capacity.

From a technical perspective, previous studies have demonstrated that floating-tire breakwaters can significantly reduce wave energy while promoting sediment deposition, making them an effective way for coastal-erosion mitigation. Laboratory and field experiments reported transmission coefficients as low as 0.036–0.20 for short waves, indicating that only a small fraction of incident wave height reaches the shoreline (Zhang and Magee, 2021; Haryani, 2022). Financial analyses also suggest that tire-based structures can be constructed for approximately only USD 4–30 per linear foot and can reduce wave heights by up to 75% under moderate sea conditions, offering a substantially cheaper alternative to conventional concrete seawalls (Hassan *et al*., 2024). Moreover, the permeable nature of tire breakwaters accelerates sediment capture, with observed reductions in near-shore current velocity of around 35% and sediment accretion reaching up to 6 cm, contributing to shoreline stabilization (Haryani, 2022). Collectively, these findings highlight the technical effectiveness, economic efficiency, and local adaptability of APO as a community-friendly solution for mitigating coastal erosion.

While the physical performance of APO structures has been well documented, assessing their long-term effectiveness requires a temporal perspective. In this context, coastal erosion analysis using remote sensing technology enables periodic observation of shoreline dynamics and evaluation of APO installation impacts over time. Remote sensing approaches for shoreline-change monitoring have been widely applied in previous studies. For instance, a multi-temporal analysis using multispectral imagery from Landsat and MODIS was conducted to detect shoreline changes in Red Sea mangrove areas between 1990 and 2022, achieving an overall accuracy of 87% (Alharbi, 2025). Similarly, Fauzunora *et al*. (2023) conducted time-series analysis to examine shoreline changes along the Indramayu coast in West Java. By integrating Landsat imagery with the DSAS, the study effectively quantified shoreline dynamics, revealing abrasion areas of 805.71 ha and accretion areas of 941.63 ha. These studies collectively demonstrate that remote sensing provides a robust and reliable framework for monitoring temporal shoreline changes and evaluating the effectiveness of coastal protection measures such as APO.

Despite this growing body of technical evidence, existing research remains heavily skewed toward physical performance, cost efficiency, and engineering design. Studies on tire-based coastal protection structures across Indonesia's northern Java coastline have primarily focused on wave attenuation efficiency and structural performance, with limited attention to the broader socio-ecological context of their implementation (Wijaya & Lasminto, 2025; Hassan & Rodrigue, 2024). However, these studies largely overlook the social dimensions of APO implementation, specifically there is limited empirical analysis of how community involvement in planning, installation, and maintenance influences the effectiveness, durability, and legitimacy of waste-tire wave breakers. Moreover, the co-benefits potential such as local employment, skill development, strengthened social capital, and improved environmental awareness—are rarely examined in a systematic manner.

Beyond community participation, a critical yet underexamined dimension is the role of CSR in supporting coastal protection initiatives. Recent CSR-related studies highlight both the potential and the limitations of CSR-funded coastal interventions. The theoretical foundations of CSR suggest that environmental and social investments can generate shared value while addressing societal challenges (Carroll, 2021; Tjahjadi *et al*., 2021; Farid and Wati, 2024). Nevertheless, existing evaluations of CSR-supported coastal infrastructure remain largely outcome-oriented and reputational, focusing on satisfaction indices and annual reporting mechanisms rather than long-term sustainability and adaptive governance. This reveals a critical gap in assessing the durability, adaptive capacity, and social embeddedness of CSR-funded coastal infrastructure beyond short-term achievements.

Based on these facts, this study aims to explore the potential integration of community-driven approaches with CSR support to establish, maintain, and monitor waste-tire wave breakers as a hybrid solution. By combining local participation, traditional knowledge, and corporate resources, this model is expected to restore coastal protection while enhancing adaptive capacity and community management (Zhang and Gu, 2021; Dressel *et al*., 2021; Heinen *et al*., 2022; Cárdenas *et al*., 2021). This study focuses on Tanjung Pakis as a critical case to examine how such integration can address intertwined ecological and socio-economic challenges in Indonesia's highly vulnerable coastal zones.

2. Methods

2.1. Theoretical Framework

2.1.1. Mainstreaming Corporate Social Responsibility (CSR) into Climate Adaptation Strategy

To ensure long-term impact and alignment with broader sustainable development goals (SDGs), CSR programs must be mainstreamed into climate adaptation strategies at both the regional and village levels. In Tanjung Pakis, where coastal erosion, ecosystem degradation, and socio-economic vulnerabilities converge, CSR must go beyond short-term philanthropic initiatives and evolve into systemic, place-based responses to climate risk. CSR initiatives should be guided by robust frameworks to ensure long-term sustainability and contextual relevance.

The concept of **Creating Shared Value (CSV)** posits that companies can enhance their competitiveness while simultaneously addressing social and environmental challenges. In this context, a tire manufacturing company supporting the installation of APO contributes not only to waste reduction but also to strengthening community resilience and local stakeholders relationships.

Similarly, the **Triple Bottom Line (TBL)** framework proposed by Tjahjadi *et al*. (2021) emphasizes that CSR should generate value across three interrelated dimensions: *people, planet*, and *profit*. The *people's dimension* involves protecting coastal livelihoods and promoting inclusive participation in decision-making processes. The *planet* dimension focuses on restoring mangrove ecosystems, reducing coastal erosion, and mitigating climate-related risks. The *profit* dimension highlights the importance of enhancing business sustainability, strengthening supply chain resilience, and improving corporate reputation. The APO initiative reflects this alignment by safeguarding local livelihood, supporting ecosystem restoration, and creating cost-effective waste management opportunities. In this way, TBL provides a strategic lens through which CSR can be aligned with climate adaptation, demonstrating that environmental sustainability and business performance can be mutually reinforcing.

In addition, at the foundation of this framework lies the widely accepted Pyramid of CSR proposed by Carroll (2021), which classifies CSR into four hierarchical layers: economic, legal, ethical, and philanthropic responsibilities, as illustrated in Figure 1. The economic layer represents society's expectation that businesses generate goods and services desired by customers in a profitable and sustainable manner. The legal layer refers to the obligation of companies to comply with laws and regulations, including those related to environmental management. The ethical dimension extends beyond legal compliance, requiring businesses to act fairly and justly in alignment with societal norms. Finally, the philanthropic layer encourages voluntary contributions to the community, such as environmental restoration or local capacity building. In the case of Tanjung Pakis, this framework supports CSR activities that span all four layers, producing economic value through tire recycling, complying with environmental standards, acting ethically in stakeholder engagement, and contributing voluntarily to climate resilience through APO installation.

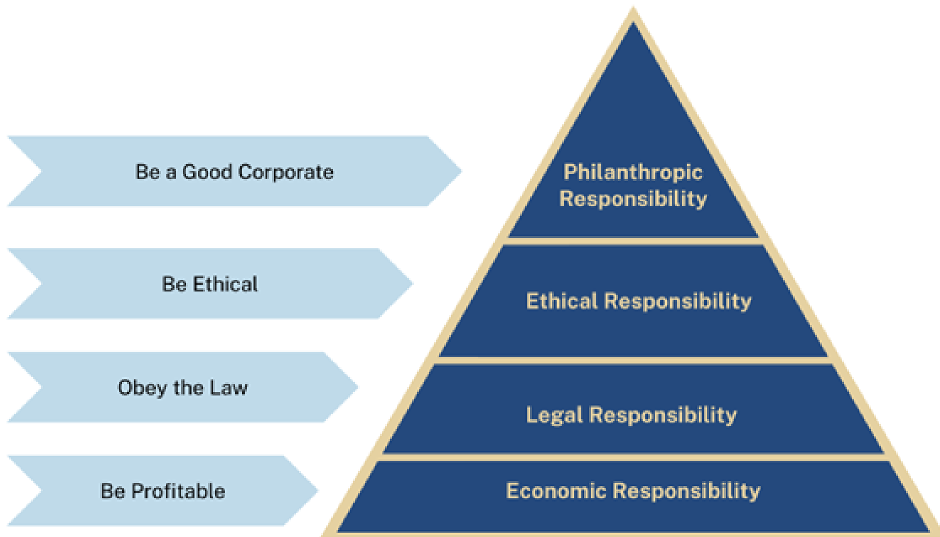

Figure 1. Carroll's Corporate Social Responsibility (CSR) Pyramid illustrating the hierarchy of corporate responsibilities within the theoretical framework of sustainable business practices

In conclusion, this integrated theoretical framework, drawing from Carroll's CSR Pyramid (Carroll, 2021), the Triple Bottom Line (Tjahjadi et.al, 1997), and Creating Shared Value (Farid and Wati, 2024), provides a comprehensive foundation for analyzing the strategic and community-inclusive role of CSR in building coastal resilience. It supports the argument that CSR, when properly designed and implemented, can transcend traditional charity-based approaches and become a transformative force in sustainable climate adaptation.

2.1.2. Remote Sensing for Shoreline Analysis

Remote sensing is defined as the science and art of acquiring information about objects, areas, or phenomena without direct contact through the analysis of acquired data (Vitousek *et al*., 2023). Satellites represent a primary technology within remote sensing, capable of capturing images of specific locations at both local and global scales with adequate spatial, temporal, and spectral resolution. This capability is crucial for visualizing changes in the Earth's surface over time and enables the monitoring of complex spatial dynamics, including shoreline changes and coastal ecosystem transformations. Recent advances in satellite-based remote sensing have further expanded its application in environmental monitoring, particularly for detecting long-term trends in coastal ecosystems such as mangrove degradation and shoreline dynamics through multi-temporal analysis (Wei *et al*., 2025).

Monitoring coastline changes using satellite data is particularly relevant in the context of mangrove ecosystems, which are highly vulnerable to erosion and land conversion. Mangroves play a vital role in maintaining coastal stability while providing essential ecosystem services such as carbon storage and protection against climate-related hazards (Ambariyanto *et al*., 2023). Therefore, remote sensing techniques using satellite data offer quantitative and time-series information necessary for analyzing changes in mangrove distribution and assessing the impacts of coastal erosion and sedimentation processes.

In practical applications, satellites like Landsat and Sentinel-2 are frequently used due to their sufficiently detailed spatial resolution for regional-scale observations, alongside temporal resolution enabling time series analysis over decades. As shown in Figure 2, each satellite has distinct spectral band characteristics, facilitating the identification of various Earth surface features, including coastal ecosystem zones and coastline changes (Singh *et al*., 2020). Another advantage of this technology is the availability of historical data that supports long-term trend analysis.

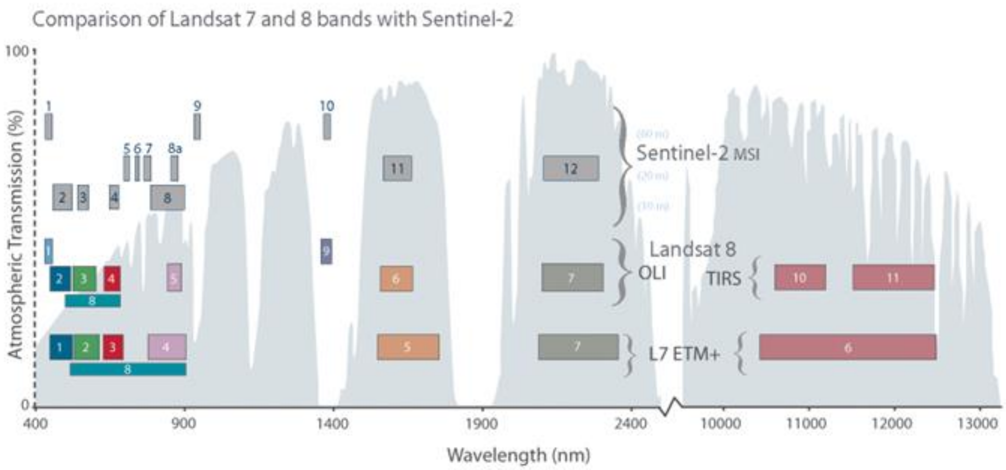

Figure 2. Comparison of spectral band configurations between Landsat 7, Landsat 8, and Sentinel-2 satellite imagery used for shoreline and coastal analysis. Source: United States Geological Survey (USGS)

The use of Geographic Information Systems (GIS) combined with remote sensing enables systematic and quantitative mapping and measurement of coastline changes. This method allows for the calculation of annual erosion or accretion rates, which is critical for adaptation and mitigation planning in coastal areas facing pressure from climate change and anthropogenic activities, such as in the Tanjung Pakis region, which is the focus of this study.

2.2. Approach

2.2.1. Location

The project site is in Tanjung Pakis Village, Karawang Regency, West Java, Indonesia (Figure 3). Geographically, the village lies along the northern coastline of Java Island, directly facing the Java Sea. Administratively, Tanjung Pakis is bordered by Tanjung Jaya Village to the west, Pakis Jaya Village to the east, and Pakis River estuarine systems to the south, while the northern boundary is defined by the open coastal waters of the Java Sea. This spatial configuration places the study area in a coastal lowland environment highly influenced by tidal dynamics, monsoonal wind regimes, and riverine sediment input.

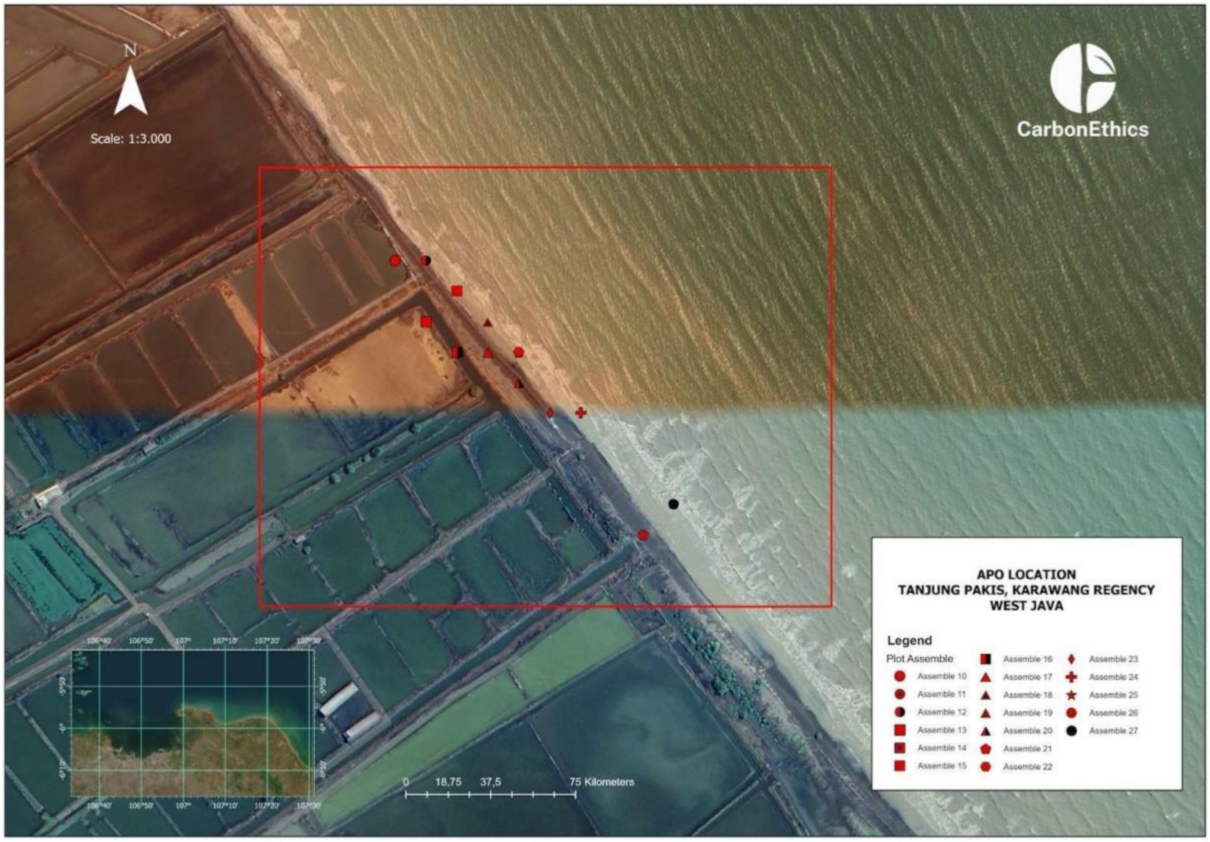

Figure 3. Location of waste-tire wave breakers (APO) installations along the coastal area of Tanjung Pakis Village, Karawang Regency, West Java, Indonesia

This location was selected due to the severe coastal erosion that has been occurring in Tanjung Pakis over the past two decades. The northern coastline of Java, including the Karawang segment where Tanjung Pakis is situated, has experienced chronic shoreline retreat driven by hydrodynamic forces, tidal currents, reduced sediment supply from upstream rivers, and accelerating land subsidence — with erosion rates along the north Java coast documented at up to 10–15 metres per year in the most severely affected segments (Solihuddin *et al*., 2021; Handiani *et al*., 2022). The erosion has resulted in significant land loss, destruction of aquaculture ponds and settlements, and increased vulnerability of local communities to coastal hazards. Moreover, the degradation of protective mangrove ecosystems has exacerbated these impacts, leaving the shoreline more exposed to wave energy and storm surges (Ambariyanto *et al*., 2023).

2.2.2. Research Flow

This study applies a Participatory Rural Appraisal (PRA) framework to engage community members in identifying local coastal challenges and co-designing interventions. PRA empowers coastal residents to apply their own knowledge in ecosystem restoration efforts. The core intervention is a hybrid approach that marries ecological and engineered solutions. One such solution is the APO, a low-cost, locally constructed structure that dissipates wave energy and enhances sedimentation. The Approach is sequenced into four stages, as shown on Figure 4.

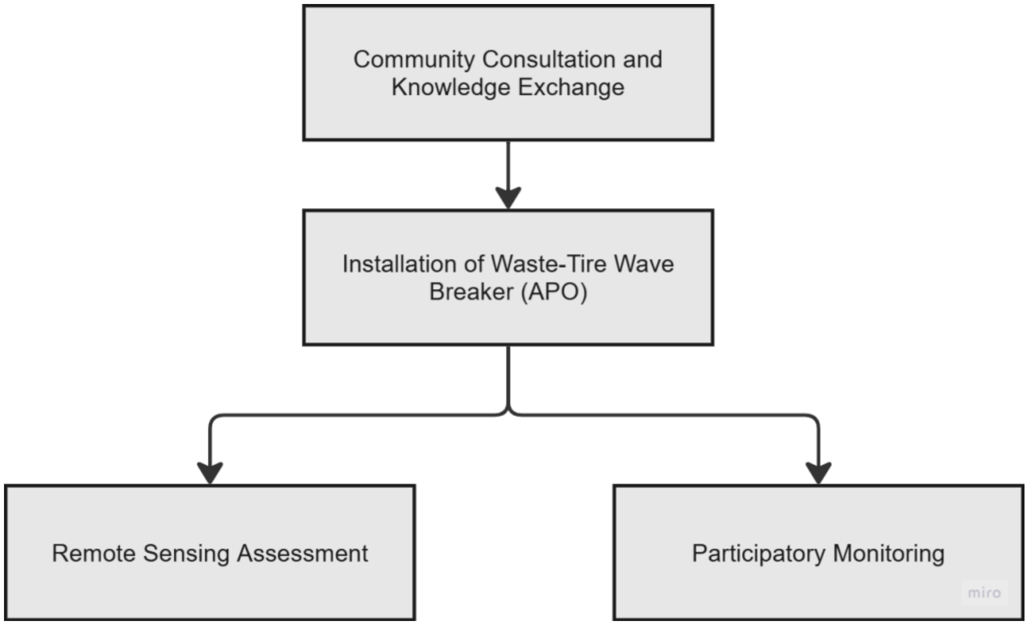

Figure 4. Research framework and implementation stages of the community-driven APO (waste-tire wave breakers) coastal protection initiative in Tanjung Pakis Village, Karawang Regency, Indonesia

- **Community Consultation and Knowledge Exchange**, Initial engagement with local community groups to identify risks, experiences with erosion, and perceptions of previous mitigation efforts;
- **Installation of APO**, installation and deployment of waste-tire wave barriers at erosion-prone coastal segments, in partnership with local labor and leadership;
- **Participatory Monitoring**, Involvement of the community in observing changes in shoreline morphology;
- **Remote Sensing Assessment**, Use of remote sensing and geospatial tools to assess shoreline changes over time and evaluate the physical impact of the intervention.

2.3. Data Collection

2.3.1. Socio-economy Data

This study applied a mixed-methods approach to assess the socio-economic impacts of the APO, combining quantitative and qualitative data to capture both economic changes and community perceptions. Quantitative data were collected through semi-structured interviews with 13 direct beneficiaries of the APO intervention. Household income data were recorded on a quarterly basis for one year before and one year after the APO installation (2023–2024). This approach enabled comparison of income trends over time and identification of livelihood changes potentially associated with improved coastal conditions. In addition, the quantitative data were analyzed descriptively and were obtained through in-depth interviews with key local stakeholders, including village-level government representatives and local workers involved in the installation and monitoring of the APO. In addition, participatory Focus Group Discussions (FGDs) were conducted with the same 13 local workers to capture collective perceptions regarding coastal safety, livelihood sustainability, ecological benefits, and maintenance challenges.

Respondents and informants were selected based on clear criteria: (i) residency in Tanjung Pakis; (ii) direct involvement in or benefit from the APO intervention; and (iii) experience of both pre- and post-intervention conditions. Qualitative data were analyzed thematically, complementing the descriptive analysis of quantitative findings to provide an integrated understanding of the APO's socio-economic impacts.

2.3.2. Remote Sensing Data

This study leverages Harmonized Sentinel-2 MSI satellite imagery spanning the 2018–2022 period as the primary data source to investigate shoreline dynamics. Initial data preprocessing is conducted through the Google Earth Engine platform, employing a cloud masking technique set to exclude images with more than 10% cloud cover, thereby ensuring the integrity and clarity of the imagery used for analysis.

Following this preprocessing, the refined satellite data undergo rigorous spatial analysis within a GIS environment. During this phase, distinct delineation between terrestrial and aquatic zones is established, facilitating the precise digitization of the shoreline as a critical spatial feature. This digitized shoreline serves as the foundation for subsequent temporal change detection.

To quantify the rate and extent of shoreline movement, the DSAS is employed. This method calculates transects orthogonal to the shoreline, enabling systematic measurement of shoreline position changes over time. The resulting endpoint rates, expressed in meters per year (m/yr), offer robust quantitative indicators of coastal erosion or accretion trends within the study area. Mathematically, the endpoint rate (EPR) is calculated as:

$$EPR = \frac{D}{T}$$

where:

D represents the linear distance between the two shoreline positions along a transect (positive for accretion, negative for erosion), and T denotes the time interval in years between the two shoreline datasets.

By integrating satellite remote sensing, cloud-based computing, and advanced GIS-based spatial analytics, this approach provides a comprehensive assessment of coastal dynamics at Tanjung Pakis (Figure 5). The derived insights are pivotal for informed coastal management, supporting adaptive strategies and mitigation efforts responsive to ongoing environmental changes.

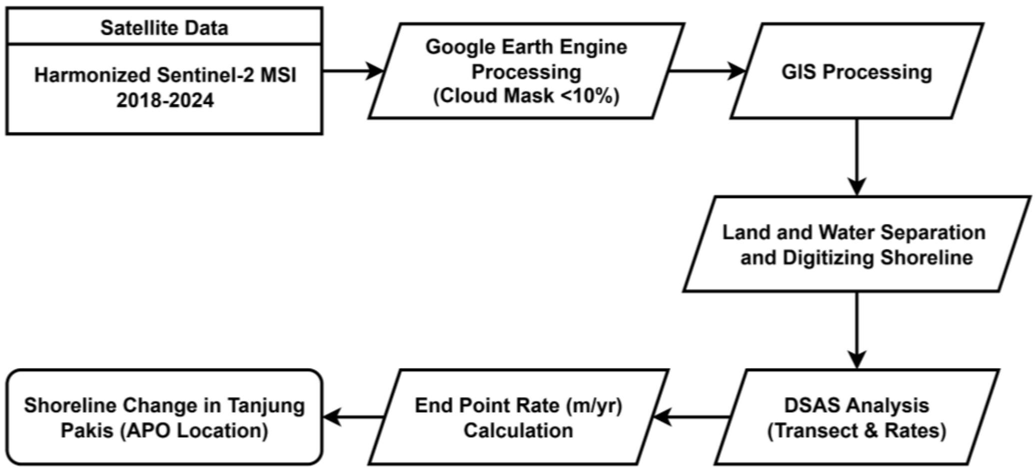

Figure 5. Remote sensing and GIS-based processing workflow for shoreline change analysis in the APO (waste-tire wave breakers) installation area of Tanjung Pakis Village, Karawang Regency, Indonesia

3. Results

3.1. Shoreline Change Assessment

Multi-temporal shoreline analysis using Sentinel-2 imagery and the DSAS was conducted for the period 2018–2024, covering two distinct phases: pre-APO installation (2018–2022) and post-APO installation (2022–2024) (Figure 6). The analysis was based on 40-metre transects, with a total of 26 transects distributed along the Tanjung Pakis shoreline. The average End Point Rate (EPR) across the full study period (2018–2024) indicated a net erosion rate of −7.56 m/yr. Table 1 presents the EPR values disaggregated by period.

Table 1. Comparison of shoreline erosion and accretion End Point Rate (EPR) values before and after APO (waste-tire wave breakers) installation in Tanjung Pakis Village, Indonesia (2018–2024)

Period	End Point Rate Erosion (m/yr)		End Point Rate Accretion (m/yr)		Average End Point Rate (m/yr)
	Highest Value	Average	Highest Value	Average	
2018-2022	-20.69	-11.45	5.20	2.95	-9.79
2022-2024	-13.56	-6.72	8.05	4.61	-5.41

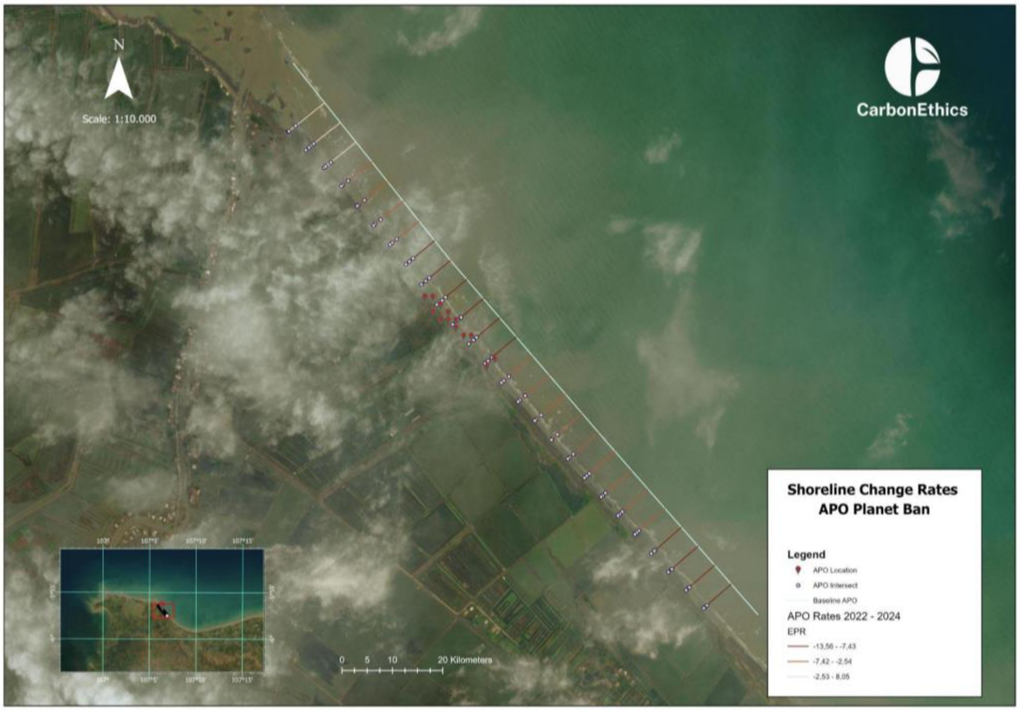

Figure 6. Spatial distribution of shoreline change rates around APO (waste-tire wave breakers) installation areas in Tanjung Pakis Village, Karawang Regency, West Java, Indonesia, based on DSAS End Point Rate (EPR) analysis for the 2022–2024 period

The results indicate a clear shift in shoreline dynamics following APO installation. The mean EPR improved from −9.79 m/yr during the pre-installation period to −5.41 m/yr during the post-installation period, representing a reduction in overall shoreline retreat of 4.38 m/yr. More specifically, the mean erosion-specific rate decreased by 4.73 m/yr, while the mean accretion rate increased by 2.85 m/yr. The most pronounced improvements were spatially concentrated in APO-installed shoreline segments, reflecting effective wave attenuation and sediment trapping by the structures. Net erosion nevertheless persisted throughout the post-installation period, indicating that APOs function as mitigation measures that reduce, rather than eliminate, chronic shoreline retreat under current conditions. Notably, the pre-installation shoreline trend, represented by the red line in Figure 6, reflects a period of significant and accelerating coastal degradation, which constituted the primary spatial rationale for selecting these segments as priority areas for APO deployment.

3.2. Community Perceptions of Coastal Change

The FGDs were conducted involving 13 community respondents to collect community perceptions about shoreline and environmental change before and after APO installation. Community members were drawn from both APO-installed and non-installed shoreline segments to enable a comparative assessment. Table 2 summarizes the principal themes and perceptions by segment.

Table 2. Forms of community participation in APO (waste-tire wave breakers) coastal protection project in Tanjung Pakis Village, Karawang Regency, Indonesia

No	Activity	Description
1	Receipt and handling of tire material	Community members managed logistics, cutting, and preparation of used tires for APO installation.
2	Planning of APO placement	Together with technical teams and local leaders, residents identified strategic locations based on wave direction and erosion levels.
3	Construction and installation	Local workers assembled and submerged APO modules following technical designs and local conditions.
4	Monitoring and damage reporting	Community members conducted periodic visual inspections and reported any structural shifts or damage.

Community from APO-installed segments reported reduced perceived wave force and less high-tide overtopping, increased local sediment deposition, and enhanced protection of fishponds, the community's primary livelihood asset from wave damage and inundation. These perceived improvements were associated with increased confidence to undertake mangrove planting and maintenance activities in the more sheltered zones behind the structures. In contrast, respondents from non-installed segments reported persistently strong wave exposure and continued shoreline retreat, with fishponds perceived as remaining at risk and little motivation for restoration activities.

Elang Laut farmer group's full engagement in all project phases shows that when local ownership is prioritized, conservation infrastructure becomes more sustainable, adaptive, and meaningful (Figure 7). This participatory model holds significant potential for replication in other coastal areas facing similar environmental and livelihood pressures.

Figure 7. Community members from the Elang Laut Farmer Group APO (waste-tire wave breakers) units in Tanjung Pakis Village, Karawang Regency, West Java, Indonesia, as part of the community-driven coastal protection initiative

3.3. Structural Performance and Technical Monitoring

Routine community-led monitoring by the Elang Laut Farmer Group identified a number of structural performance issues during field inspections of APO units. Table 3 presents the observations recorded and their probable causes.

Table 3. Issues identified during participatory monitoring of APO (waste-tire wave breakers) structures in Tanjung Pakis Village, Karawang Regency, Indonesia

Observation	Potential Cause
Binding ropes of three units detached	Suspected collision with fishing boats during high tide or strong wave impact
APO structures not clearly visible at high tide	Lack of surface markers, increasing collision risk
Lack of unit identification markers	Initial proposal to install numbered stakes not yet implemented

The documented issues such as binding rope detachment, submerged visibility at high tide, and absence of unit identification highlight vulnerabilities in structural durability, navigational safety, and monitoring traceability. Based on these findings, the Elang Laut Farmer Group and project facilitators developed a set of improvement recommendations, presented in Table 4.

Table 4. Recommended improvements for APO (waste-tire wave breakers) system based on field observations and stakeholder feedback in Tanjung Pakis Village, Karawang Regency, Indonesia

Improvement Area	Recommendation
Structural durability	Use reinforced rope or chain materials for better tidal resistance
Visual identification	Add floating buoys or netting to mark APO locations and increase boat safety
Monitoring and tracking	Implement stake-based unit numbering system for damage reporting and mapping
Fisher engagement	Conduct orientation sessions with fishers to reduce navigation-related damage

3.4. Socio-economic Co-benefits and CSR-Supported Implementation

The APO installation project was financed through a Corporate Social Responsibility (CSR) arrangement with Planet Ban, which supplied waste tires as the primary construction material, operationalising a circular economy approach that converts an environmental liability into functional coastal infrastructure. As illustrated in Figure 8, the CSR-donated waste tires were transported by local community members using traditional wooden boats directly to the installation sites, reflecting the full integration of local labour into every stage of the APO supply chain from material acquisition to field deployment. A total of 13 local workers were directly engaged in APO installation and monitoring, of whom 53.85% were youth. Table 5 summarises the key economic outcomes recorded between the pre-APO (2023) and post-APO (2024) periods.

Figure 8. CSR support from Planet Ban for the implementation of APO (waste-tire wave breakers) coastal protection structures in Tanjung Pakis Village, Karawang Regency, Indonesia

Table 5. Socio-economic outcomes of local workers involved in APO (waste-tire wave breakers) coastal protection project in Tanjung Pakis before (2023) and after installation (2024)

Indicator	Pre-APO (2023)	Post-APO (2024)	Change
Average monthly income	Rp 4,500,000	Rp 5,000,000	+Rp 500,000 (+11.1%)
Annual income gain per person	—	—	+Rp 6,000,000
Total workers directly engaged	—	13 workers	—
Youth proportion of workforce	—	53.85%	Majority youth

Between 2023 and 2024, the average monthly income of participating workers increased by Rp 500,000 from Rp 4,500,000 to Rp 5,000,000 representing an average increase of 11.1%, equivalent to an additional Rp 6,000,000 per person annually. The income improvement was primarily driven by improved protection and enhanced productivity of fishponds in APO-installed zones, combined with direct wage employment in APO construction and maintenance activities. CSR funding was critical in enabling both the physical construction of APO structures and sustained local labour involvement, thereby strengthening community ownership and ensuring project continuity beyond the initial installation phase.

4. Discussion

4.1. APO Effectiveness in Reducing Shoreline Erosion

The DSAS results demonstrate a statistically meaningful reduction in shoreline erosion following APO installation. The mean EPR improved from −9.79 m/yr (2018–2022) to −5.41 m/yr (2022–2024), a net improvement of 4.38 m/yr, while the mean accretion EPR simultaneously increased from 2.95 m/yr to 4.61 m/yr. These findings are consistent with prior studies documenting the capacity of permeable wave-breaking structures to attenuate wave energy, stabilise substrates, and promote sediment accretion in erosion-prone coastal zones (Alharbi, 2025; Fauzunora *et al*., 2023; Arifanti *et al*., 2025; Wei *et al*., 2025). The spatial concentration of improvements in APO-installed shoreline segments confirms that the observed geomorphological response is attributable to the structures, rather than to exogenous environmental variability, and reflects the effectiveness of APOs as localised wave attenuators and sediment traps.

Nevertheless, net erosion persisted throughout the post-installation period, indicating that current APO deployment has not fully reversed the chronic shoreline retreat affecting Tanjung Pakis. This outcome is consistent with the broader context of coastal degradation in the northern Java coast, where historical mangrove conversion to aquaculture has substantially reduced the natural wave buffering and sediment stabilisation capacity of the coastline (Arifanti *et al*., 2025; Wei *et al*., 2025). Contributing factors beyond APO installation, including seasonal variation in wave energy, bathymetric and morphological heterogeneity, water depth, and the residual density and extent of mangrove cover are acknowledged as co-determinants of observed shoreline dynamics. Future research should employ wave attenuation modelling and hydrodynamic datasets alongside DSAS to partition the relative contributions of structural and ecological variables to shoreline change, thereby improving the precision of coastal management assessments.

4.2. APOs as Complementary Measures within a Hybrid Coastal Protection Framework

The findings support situating APOs within a hybrid coastal protection framework, wherein engineered wave-breaking structures and ecosystem-based solutions are understood to function synergistically rather than as alternatives. Empirical evidence from coastal rehabilitation sites in Bengkalis and Bintan (Herdiwan *et al*., 2022) similarly indicates that APOs function primarily to reduce wave energy and stabilise substrates in order to support mangrove seedling survival during early restoration phases, rather than as standalone long-term protection measures. This is consistent with the present study, where APO structures created more favourable hydrodynamic and sedimentary conditions in sheltered zones, which community members associated with improved conditions for mangrove planting.

This interpretation is further supported by previous studies on integrated mangrove landscape design and coastal disaster mitigation, which emphasise that simple and user-friendly APO-based hybrid engineering approaches can facilitate mangrove rehabilitation while simultaneously supporting coastal resilience and ecotourism development (Ilhami *et al*., 2021). Within this framework, mangrove ecosystems function not only as natural coastal barriers but also as *sediment traps* capable of restoring eroded coastlines and improving environmental quality through pollutant absorption, including heavy metals and other contaminants. These ecological functions reinforce the role of APOs as enabling structures that support broader ecosystem recovery processes rather than acting as permanent standalone coastal defences.

Accordingly, APOs should not be regarded as permanent substitutes for ecosystem-based coastal protection. Their effectiveness as complementary engineering measures is maximised when deployment is explicitly linked to mangrove restoration targets, spatially coordinated with revegetation activities, and embedded within a long-term coastal management strategy that prioritises ecosystem recovery and resilience. This interpretation is supported by the FGD results, which indicate that enhanced perceived protection in APO-installed zones increased community confidence to invest in mangrove planting, a feedback dynamic between structural intervention and ecosystem restoration behaviour that merits explicit attention in future programme design. APOs are therefore best understood as transitional interventions that bridge the gap between a highly erosive, unprotected shoreline and a stabilised substrate capable of sustaining mangrove recovery, provided that structural integrity is maintained through proper installation standards, performance monitoring, and routine maintenance.

4.3. Community Perceptions, Fishpond Livelihoods, and Local Validation of Findings

The consistency between FGD findings and DSAS measurements constitutes an important methodological result. The spatial correspondence between perceived wave reduction, increased sediment deposition, and enhanced fishpond protection in APO-installed segments contrasted with persistent exposure and retreat reported in non-installed segments reinforces the conclusion that APO structures deliver meaningful, spatially discrete coastal protection. This alignment between quantitative geomorphological evidence and qualitative community perception validates the use of participatory FGD data as a complementary diagnostic tool in coastal management assessments (Dressel *et al*., 2021; Zhang and Gu, 2021), and supports a mixed-methods approach for evaluating hybrid coastal interventions in data-scarce tropical environments

The centrality of fishpond protection as a perceived co-benefit of APO installation reflects the livelihood context of the Tanjung Pakis community, where aquaculture represents the primary income-generating activity. The literature on community-based coastal adaptation consistently demonstrates that the uptake of protective interventions is shaped by their perceived relevance to local livelihoods and productive assets (Dressel *et al*., 2021; Heinen *et al*., 2022). In this context, the improved perceived protection of fishponds from wave inundation and overtopping as reported by FGD participants in APO-installed zones is likely a proximate driver of the observed increase in household income, which averaged 11.1% between 2023 and 2024. The close alignment between structural protection, fishpond productivity, and household income provides a concrete socio-economic rationale for continued APO investment that extends beyond the biophysical case for shoreline stabilisation.

4.4. Technical Limitations and Adaptive Improvement Pathways

Community-led monitoring identified three principal structural vulnerabilities in the current APO deployment: binding rope detachment attributed to vessel collision during high tide, limited visibility of submerged units at high water, and the absence of systematic unit identification markers. These issues reflect broader challenges documented in prior assessments of tire-based coastal structures, where structural integrity, navigational safety, and monitoring capacity are recognised as recurring limitations requiring proactive engineering and institutional responses (Zhang and Magee, 2021; Wijaya & Lasminto, 2025).The cautionary precedent of the Osborne Reef in Florida (Perricone *et al*., 2023) where inadequate design and weak governance resulted in structural failure and ecological harm underscores that the long-term success of tire-based coastal protection depends critically on robust monitoring, adaptive maintenance, and clear institutional accountability.

The community-generated recommendations, installation of *waring* netting as combined reinforcement and visual marker, adoption of a stake-based unit numbering system, and targeted engagement of local fishers to reduce navigation-related structural damage reflect an adaptive management approach that integrates local ecological knowledge and operational experience into iterative design improvement. The proposal to install numbered identification stakes, developed by Elang Laut Farmer Group but awaiting implementation by project governance partners, illustrates both the potential and the institutional limitations of community-driven monitoring: communities can identify technical deficiencies and generate practical solutions, but implementation requires responsive institutional support from CSR partners and facilitating organisations. Addressing this gap is essential for ensuring that the structural resilience and long-term effectiveness of APO deployments are maintained beyond the initial installation phase.

4.5. Socio-economic Co-benefits, CSR Funding, and Multi-stakeholders Governance

The 11.1% average increase in monthly income among directly employed workers represents a substantive, if localized, socio-economic co-benefit of the APO initiative. Comparable findings from community-based coastal adaptation and ecosystem restoration programs, have documented short- to medium-term income gains through wage labor, skill development, and enhanced protection of productive coastal assets (Wang *et al*., 2022; Hassan *et al*., 2024), confirming that participatory coastal infrastructure investments can simultaneously deliver livelihood and environmental dividends. The predominant engagement of youth — comprising 53.85% of the workforce — is particularly significant given the declining coastal tourism and increasing pressure on fisheries-based livelihoods in the northern Java coast, where climate-related stressors are projected to intensify. Grounded in participatory frameworks, youth-centered approaches facilitate meaningful involvement in decision-making, contribute to the development of individual and collective capacities, and promote intergenerational collaboration, which together enhance the long-term adaptive stewardship of coastal infrastructure and ecosystems (Rauhaus, 2021).

The CSR-supported funding model, in which Planet Ban supplied waste tires as the primary construction material, exemplifies the circular economy principle of transforming waste streams into functional resources for environmental and social benefit (Hassan *et al*., 2024). This approach simultaneously reduces the environmental burden of tire disposal, lowers construction costs, and creates a replicable model for leveraging corporate waste management obligations as a mechanism for financing community-led coastal protection. Recent studies have confirmed that tire-based structures can perform effectively in coastal protection contexts when supported by appropriate engineering design and environmental safeguards (Zhang and Magee, 2021; Wijaya & Lasminto, 2025), lending technical credibility to the material choice made in this project.

The multi-stakeholder governance configuration underpinning the Tanjung Pakis intervention integrating CSR funding from Planet Ban, facilitation by CarbonEthics as an intermediary organization, and community-led implementation by the Elang Laut Farmer Group reflects best practices in sustainable coastal resilience governance (Bianchi *et al*., 2021; Avoyan, 2023; Cárdenas *et al*., 2021; Hovardas, 2021). CarbonEthics' intermediary role in translating financial and technical inputs into locally appropriate actions, delivering capacity-building programs, and establishing monitoring and evaluation mechanisms is consistent with findings from multi-stakeholders environmental governance research emphasizing the critical importance of facilitative organizations in bridging corporate objectives with community needs and ensuring transparency and adaptive learning (Asio *et al*., 2026; Avoyan, 2023; Hovardas, 2021). At the community level, Elang Laut's assumption of responsibility for ongoing monitoring, maintenance, and adaptive design advocacy demonstrates the value of investing in local organizational capacity as a foundational component of coastal resilience programming, consistent with empirical evidence that community-led implementation strengthens ownership, improves maintenance performance, and enhances adaptive capacity (Dressel *et al.*, 2021; Heinen *et al*., 2022; Zhang and Gu, 2021).

Collectively, these findings demonstrate that APOs function most effectively as complementary engineering measures that support ecosystem-based restoration rather than as long-term substitutes for it. When integrated within a community-driven approach supported by CSR funding, intermediary facilitation, and adaptive monitoring, APOs offer a viable hybrid strategy for strengthening coastal resilience in vulnerable tropical environments facing chronic erosion, livelihood insecurity, and institutional resource constraints. The Tanjung Pakis model holds significant potential for replication in comparable coastal contexts across the northern Java coast and more broadly across Southeast Asia, provided that implementation is accompanied by clear linkages to mangrove restoration targets, sustained institutional commitment, and explicit integration into wider coastal management strategies.

5. Conclusions

This study confirms that the integration of community-driven approaches and CSR support in the implementation of APO provides an effective hybrid coastal defense strategy in Tanjung Pakis. The APO installation successfully reduced shoreline retreat by approximately 4.73 m/year and increased accretion by 2.85 m/year, demonstrating its effectiveness in supporting coastal stabilization and mangrove restoration. Community participation, including the incorporation of local knowledge and youth involvement, strengthened local ownership and supported the continuity of maintenance and monitoring activities. In addition, CSR support contributed significantly to infrastructure provision, community capacity building, and operational sustainability. The intervention also generated socio-economic co-benefits, reflected in an 11.1% increase in community income, indicating that APO functions not only as a coastal protection measure but also as a livelihood-enhancing strategy. Overall, the multi-stakeholder hybrid model developed in this study offers a scalable and context-sensitive framework for addressing coastal erosion in northern Java and other erosion-prone coastal regions in Southeast Asia.

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